Optimization of the processing of bio based polymer sustainable products

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ABSTRACT: Polylactic Acid (PLA) is processed by injection moulding technology. The main aim of this study is to provide guidelines for mould and part design, namely to cope with the shrinkage effect and the ejection forces related to the use of bio based polymers. Furthermore optimization of the overall process will be investigated as well as the influence of different parameters to the process and product properties. Draft angle, mould temperature and holding pressure will be related to the ejection forces and the level of shrinkage that occurs.

1 INTRODUCTION

In recent years, growing attention has been focused on polymers derived from renewable resources (Van de Velde and Kiekens 2002; Nair and Laurencin 2007). Stimulated mainly by the unpredictable crude oil price fluctuations, numerous investigations are aimed at developing good alternatives for the current fossil-based polymers. This research aims at producing bio based sustainable products, providing guidelines for optimization of the overall process, from materials to processing and mould design. Polylactic acid, the current leader of the bio based polymers, is selected to perform the tests (Garlotta 2001). In later stages of this research, other materials will also be explored, such as polyhydroxybutyrates (Madison and Huisman 1999; He, Cheung et al. 2001).

2 MATERIALS AND METHODS

2.1 *Materials*

The used PolyLactic Acid, Ingeo™ 3052D is provided by NatureWorks LLC. It has a melt flow rate (MFR) of 14 g/10 min (210 °C/2,16 kg, ASTM D1238), a peak melt temperature from 145 to 160 degrees and a glass transition temperature (Tg) of 55-60°C. As reference material, the homopolymer polypropylene PP 575P grade from Sabic was used. This is a general purpose injection moulding grade with a consistent processability. It has a MFR of 11 g/10min (230 °C/2,16 kg, ASTM D1238), a process temperature range from 200 °C to 225 °C and a mould shrinkage of 1,2 % to 2,5 % depending on wall thickness and processing properties. Furthermore, both materials are approved for food contact applications.

2.2 *Test mould*

To be able to evaluate the shrinkage and ejection behaviour of PLA, a mould was designed to measure these values in a consistent manner. A cup-like shape form provides a good basis to evaluate both parameters. To obtain a good flow inside the mould cavity, there were no runners used, thus avoiding weld lines on the product. The draft angle of a mould can influence the ejection forces needed, therefore the mould is provided with three different mould inserts with a draft angle of one, two and three degrees.

2.3 *Methods*

In order to investigate the influence of the processing parameters on the ejection and shrinkage behaviour, a well-known reference material was selected. Polypropylene (PP) was chosen to be compared to PLA. To avoid premature degradation of the PLA, a heated hopper was applied, preventing moisture uptake. For each set of parameters, 50 cups were made. The nozzle temperature has not been changed throughout the experiments. For PP and PLA the machine nozzle temperature was respectively set to 230 °C and 210 °C, the heated tube temperature was 270 °C for both materials.

3 PROCESS PARAMETERS

When utilizing injection moulding as a processing technique for polymers, different process parameters can be influenced. Draft angle, holding pressure and mould temperature are the ones that are assumed to have the greatest effect on the shrinkage and ejection behaviour.

3.1 *Draft angle*

When designing a mould for injection moulding, the draft angle is a very important factor influencing the ejection behavior (Yan and Tan 2004). While the polymer is cooling down, densification occurs, creating a shrinkage effect onto the core of the mould. When the draft angle is too small, high ejection forces are needed and damage of the part could occur. Most polymers have an advised draft angle, however in the case of PLA, little information is available. Therefore the mould was designed with an interchangeable insert with a draft angle of one, two and three degrees.

3.2 *Holding pressure*

After the mould cavity is completely filled, holding pressure is applied to compensate the shrinkage effect. In this study, different holding pressures are applied to verify their influence (Pomerleau and Sanschagrin 2006).

3.3 *Mould temperature*

When the polymer flow comes in contact with the cold mould, the polymer starts to solidify. Densification of the polymer occurs, creating the shrinkage effect. Changing the mould temperature influences the solidification rate, the crystallization and thus the shrinkage.

3.4 *Ejection forces*

The ejection force is the one needed to eject the part out of the mould after solidification. Due to cooling, the polymer will shrink onto the core of the mould, thus making an ejector system necessary. This system has to be able to generate enough force to eject the part. While designing an ejector system, determination of these forces is inevitable. Equation 1 gives an indicative calculation for the ejection force (Pontes and Pouzada 2004; Pontes, Pouzada et al. 2005).

$$Fe = \mu \, . p \, . A \qquad (1)$$

Where Fe = ejection force (N); µ = static friction coefficient; p = contact pressure perpendicular to the core (N/mm²); A = contact surface with the core (mm²).

4 EXPERIMENTAL SET-UP

4.1 *Machine Set-up*

In this study a hydraulic injection moulding machine, Engel 80T, is used to perform the tests. It is provided with a heated hopper, and a universal screw of 35 mm. To avoid material from solidifying at the gate, a heated nozzle is used and no material is lost in ‘useless’ runner channels. The residence time is also reduced, making it ideal for bio based polymers, where residence time is crucial to avoid degradation (Van Cleemput 2012).

4.2 *Cup shape*

A test product is developed for evaluating the shrinkage and ejection behavior of different polymers. The cup-like shape is chosen because of the uniform flow. This way, the shrinkage is not influenced by weld lines. Three different inserts are designed, with a draft angle of one, two and three degrees. Therefore, the influence of the angle on the ejection forces can be monitored. In Figure 1, an example of an insert is shown.

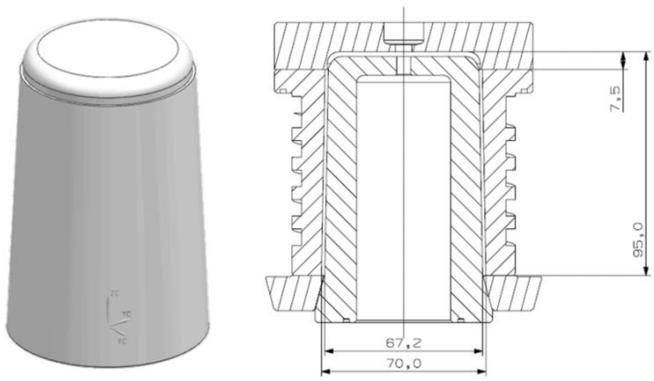

Figure 1. Mould insert with 3° draft angle.

4.3 *Sensor layout*

To be able to collect information about the injection process and the ejection behaviour, different sensors are incorporated in the mould. Four sensors are placed, which measure pressure and temperature in the nozzle, pressure in the cavity, mould temperature and ejection force. All parameters are processed by a data acquisition unit and then analyzed with Dataflow software from Kistler.

5 DATA ACQUISITION

5.1 *Obtaining ejection forces*

The ejection forces are measured with a load cell connected between the ejector piston of the injection machine and the mould. During each injection cycle, the ejection forces are monitored. An example is given in Figure 2.

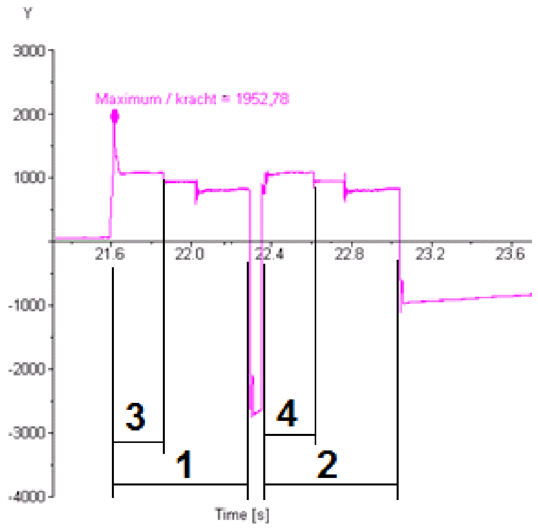

Figure 2. Ejection forces during injection cycle.

The registered data can be divided into different segments, as illustrated in Figure 2. The ejection unit is moved forward two times during each injection cycle. The first ejection (1) and the second ejection (2) consist of two regions. When the part is ejected, different forces, such as ejection force and friction are registered. The ejection force itself can be monitored in region (3). Following this region, is the transfer from ejection force to sliding of the mechanism, known as the mould ejection friction force. During the second ejection, the part should already be out of the mould. Therefore, no ejection force is noticed. The residual peaks in region (4) are caused by the friction force of the mechanism, and by switchover from forward to backwards movement of the ejector mechanism.

As for the actual ejection force, this can be calculated by subtracting the baseline from the peak in region (3). This way, the peak consists of the static friction (see equation 1).

5.2 *Measuring shrinkage level*

The shrinkage of the different cups was monitored by measuring them on a Mitutoyo BHN 305 3D-measuring bench. The cups were measured on 3 dimensions: Height, diameter and wall thickness. To ensure correct data for the diameter, each cup was placed upside down, and then measured at exactly the same height. Taking into account the shrinkage in the longitudinal direction, the diameter values obtained at that specific height needed to be recalculated. To avoid the influence of post shrinkage, all the cups were measured exactly 2 weeks after production at a room temperature of 20°C.

6 RESULTS AND DISCUSSION

6.1 *Shrinkage*

By maintaining the same mould temperature (20°C) throughout the different runs, the influence of the holding pressure on the shrinkage level of the different dimensions can be analyzed. The influence on the diameter and the height is shown in Figure 3 and 4. The diameter represents the shrinkage perpendicular to the flow path, while the height gives the shrinkage in the direction of the flow path.

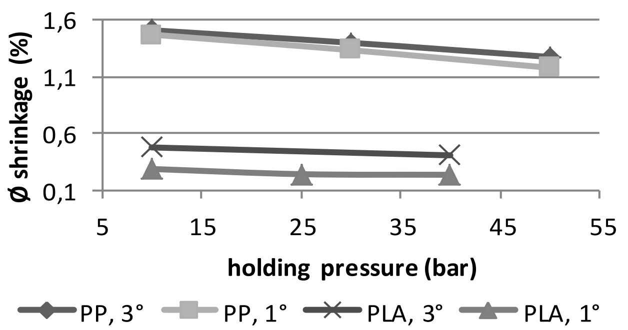

Figure 3. Diameter shrinkage vs. holding pressure.

For both PP and PLA, a decrease of the shrinkage effect can be noticed, with increasing holding pressure (Pomerleau and Sanschagrin 2006). Due to this pressure, more materials gets pressed into the mould, which compensates the shrinkage effect. The higher the applied pressure, the more material inside the mould, the lower the resulting shrinkage level.

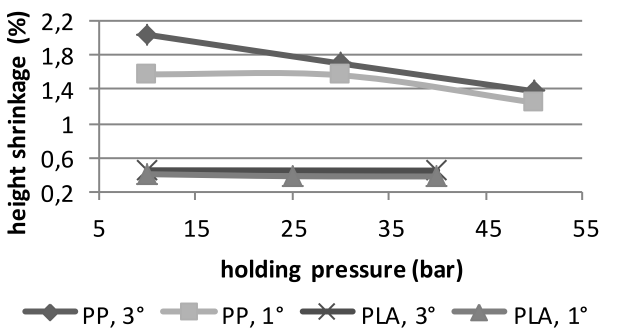

Figure 4. Height shrinkage vs. holding pressure.

The overall shrinkage for PP in the direction of the flow is higher than the shrinkage perpendicular to the flow. The higher shrinkage rate is probably caused by the orientation of the polymer chains and to the constrain effect caused by the core. The values for PLA are in the same range for both directions.

Although, the values are also higher for the shrinkage of the height. The difference in shrinkage of PLA and PP will influence the ejection forces. As the global shrinkage for PP is higher, a higher ejection force is expected.

By changing the draft angle of the insert from 3 degrees to 1 degree, lower shrinkage levels are measured. It is expected that this lower shrinkage occurred due to some minor differences in the processing conditions. Further research is needed to clarify this effect.

6.2 *Ejection forces*

The mould temperature for PP was set at 20 and 60 degrees Celsius. The different temperature settings have an influence on the flow and the cooling behaviour of the polymer melt. Higher mould temperatures will create a slower cooling and therefore solidification of the polymer melt, resulting in a

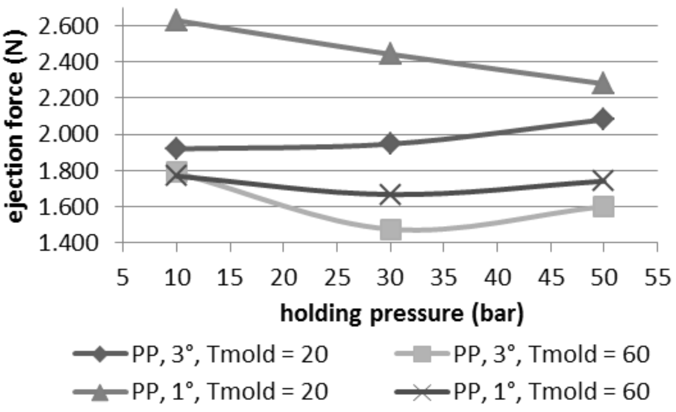

Figure 5. Ejection force vs. holding pressure for PP.

higher crystallinity. The crystallization is the main reason why the polymer suffers from a shrinkage effect.

As illustrated in Figure 5, the ejection forces for a draft angle of 1 degree are higher than the forces for 3 degrees at both mould temperatures (Cedorge and Colton 2000). The ejection forces at a mould temperature of 60°C are lower, because the polymer is not completely cooled down, making it more flexible and easier to eject.

The ejection behaviour of PLA is only monitored at a mould temperature of 20°C. Higher mould temperatures were tried, to influence the crystallinity, but these runs weren’t successful, as the part got stuck on the mould cavity, rather than staying on the core of the mould. This made it impossible to eject the part.

The curves for PLA show a similar trend as those for PP, shown in Figure 6. Although PLA is less vulnerable for shrinkage effects, the values are in the same range for both materials. Further research is needed to clarify these results.

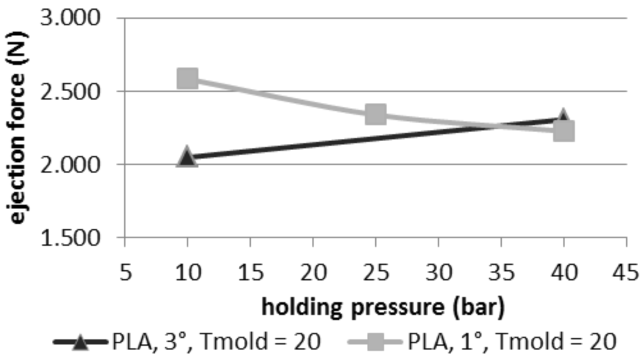

Figure 6. Ejection force vs. holding pressure for PLA.

7 CONCLUSIONS AND FUTURE WORK

After producing 50 parts of each material, with both the 1 degree and 3 degrees insert, the following relations could be determined for both materials:

- Increasing the holding pressure results in a decrease of the ejection force, and lowers the shrinkage;
- Increasing the mould temperature results in a lower ejection force, but increases the post-shrinkage;
- Increasing the draft angle results in a decrease of the ejection force.

The shrinkage follows the same trend for both materials, taking in mind the different shrinkage ratios. The measured ratios are in line with those mentioned on the datasheets. For the used PLA and PP, this is respectively 0,3 % - 0,5 % and 1,2 % - 2,5 %.

Future research will involve further investigation of the ejection and shrinkage behaviour, as well as degradation and morphology studies. This work will be conducted in collaboration with the Institute for Polymers and Composites IPC, Department of Polymer Engineering, University of Minho.

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